Polarimetric Aerosol Retrievals

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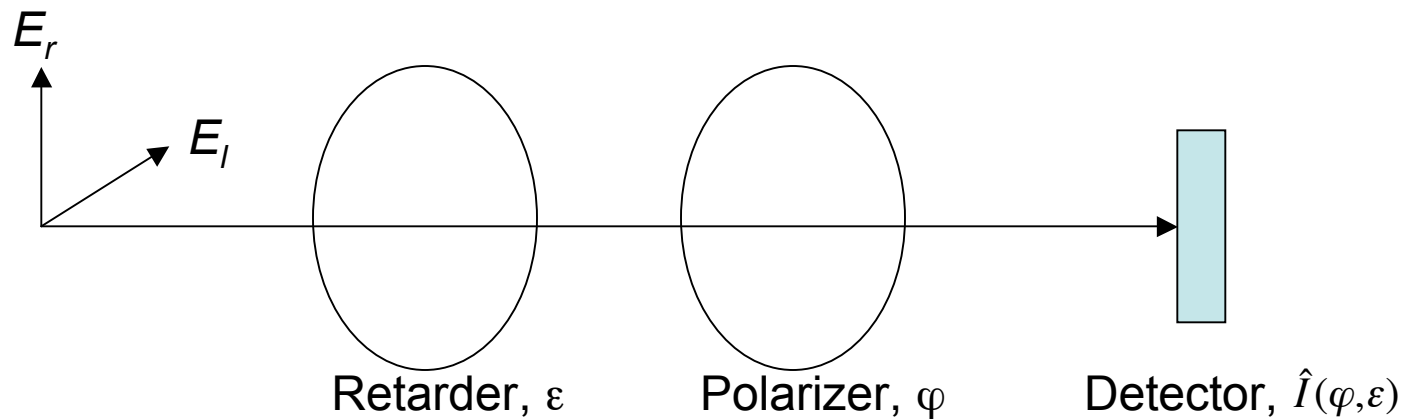
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Overview

- Introduction
- Retrieval Goals
- Retrieval Theory
  - Spatial, spectral, accuracy, calibration issues.
- Retrieval Process
  - Assumptions and approximations
- Retrieval Weaknesses
- Improvements in ACE

Introduction

– **Definitions**

E_r

E_l

Retarder, ε Polarizer, φ Detector, $\hat{I}(\varphi,\varepsilon)$

Stokes Vector

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} \langle E_l E_l^* + E_r E_r^* \rangle \\ \langle E_l E_l^* - E_r E_r^* \rangle \\ \langle E_l E_r^* + E_r E_l^* \rangle \\ -i\langle E_l E_r^* - E_r E_l^* \rangle \end{bmatrix} = \begin{bmatrix} \hat{I}(0°,0) + \hat{I}(90°,0) \\ \hat{I}(0°,0) - \hat{I}(90°,0) \\ \hat{I}(45°,0) - \hat{I}(135°,0) \\ \hat{I}(45°,\pi/2) - \hat{I}(135°,\pi/2) \end{bmatrix}$$

Degree of Linear Polarization, Angle of Polarization

$$\mathrm{DoLP} = \frac{\sqrt{Q^2 + U^2}}{I} \quad, \quad \mathrm{AoP} = \tan(2\chi) = U/Q$$

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Introduction

– **Definitions**

- Remote measurements of the polarized radiance (Stokes vector) of scattered sunlight can be expressed as:

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \frac{\mu_0}{\pi r^2} \begin{bmatrix} R_{11} & R_{21} & R_{31} & R_{41} \\ R_{12} & R_{22} & R_{32} & R_{42} \\ R_{13} & R_{23} & R_{33} & R_{43} \\ R_{14} & R_{24} & R_{34} & R_{44} \end{bmatrix} \times \begin{bmatrix} F_0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

where F_0 is the solar flux, r is the sun-earth distance in AU, $\mu_0 = \cos(\theta_0)$ and θ_0 is the solar zenith angle. The reflectance usually considered in remote sensing is R_{11}

- Since circular polarization of sunlight scattered by all natural targets is negligible we define the polarized reflectance (R_P) to be:

$$R_P = \sqrt{R_{12}^2 + R_{13}^2}$$

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Retrieval Goals

– Direct Radiative Forcing

Effective climate forcings (W/m^2) (1880–2003)

Forcing agent	Forcing (W/m^2)
Solar irradiance	0.22 (x2)
Aerosols	
Black carbon	0.43
Reflective	– 1.05
Indirect effect	– 0.77
Total aerosols	– 1.39 ± 0.7
All forcings	1.80 ± 0.85

Hansen *et al*., *Science* **308**, 1431–1435 (2005) - magnitude of current and historic variation in aerosol forcing has consequences for the equilibrium state of the energy and water cycles.

Retrieval Goals

- Direct Radiative Forcing
  - Bimodal tropospheric aerosol with:
    - Optical thickness
    - Complex refractive index
    - Size (effective radius and effective variance)

  for each mode.

  - Any mission dedicated to the study of tropospheric aerosols has to assume a large volcanic eruption will occur during the course of the mission.
    - The ability to independently characterize and retrieve the properties of stratospheric aerosols is therefore needed.

- Indirect Radiative Forcing
  - Cloud droplet size distribution (DSD, effective radius and effective variance at cloud top).
    - Techniques that attempt to estimate cloud physical thickness and number concentration using adiabatic assumptions are completely invalid if the DSD is bread at cloud top.

Retrieval Theory

– Spatial

- Resolution of a few km is acceptable since aerosols are much more strongly polarizing than clouds.
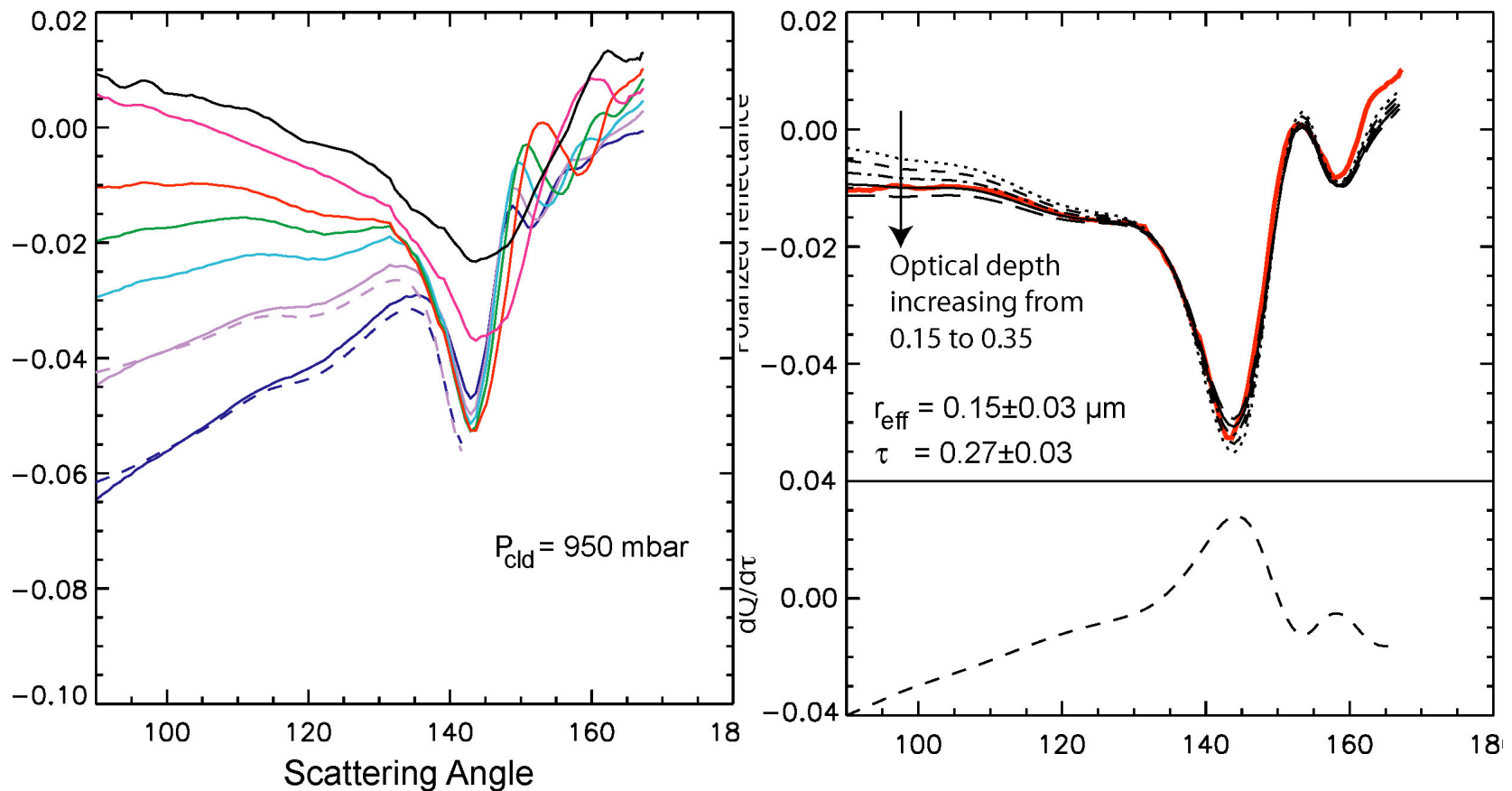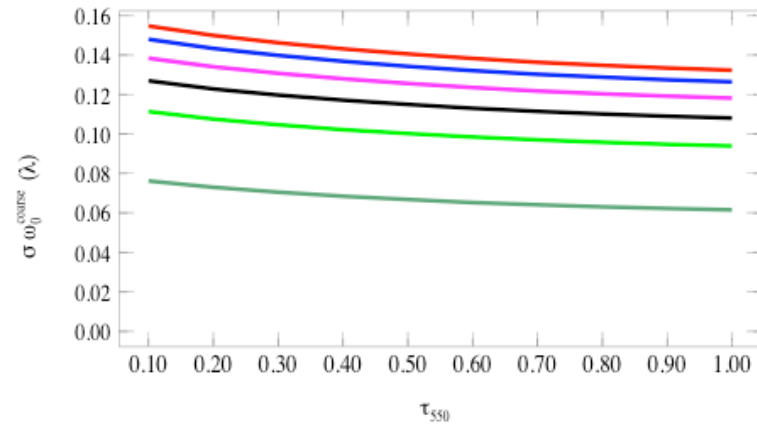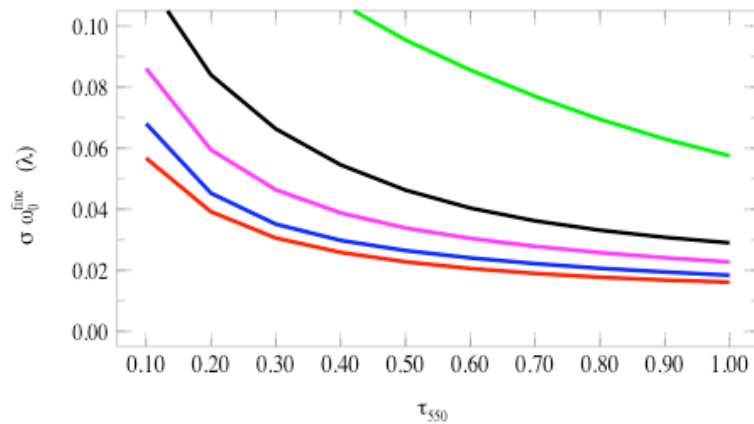
Retrieval Theory

– Spectral

- Spectral bands in the blue/UV are essential to estimate aerosol absorption and vertical extent over land and to allow for the differentiation between ocean color and aerosol absorption over ocean.
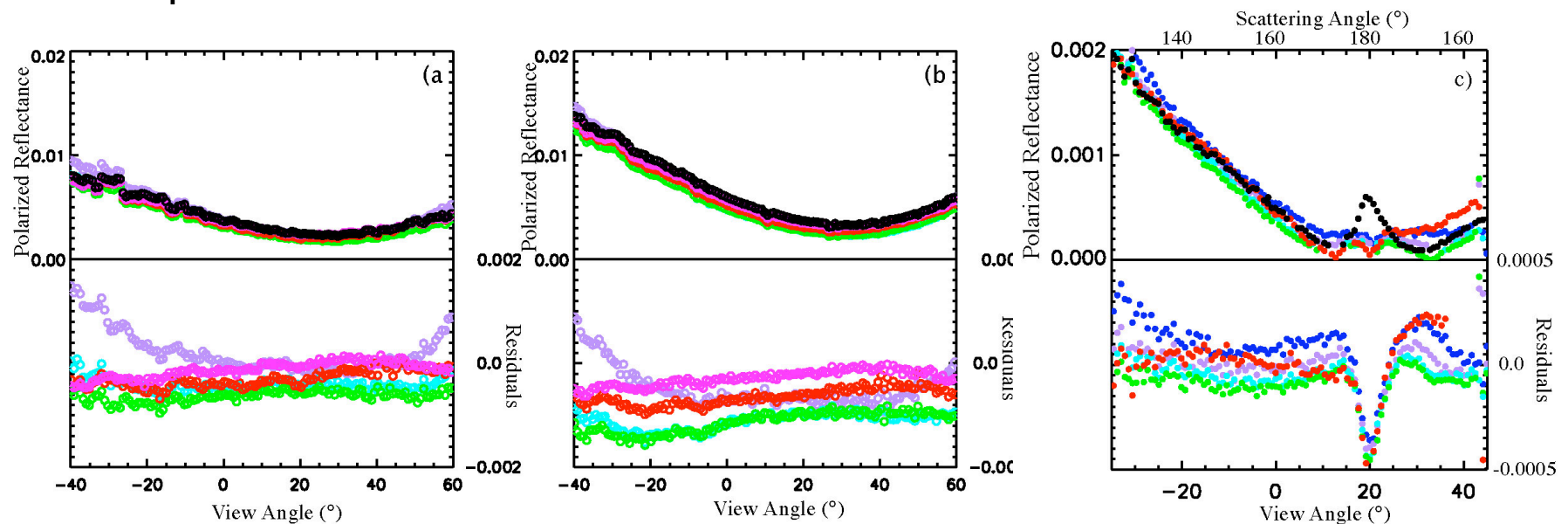
Retrieval Theory

– Spectral

  • Spectral bands in the Short-Wave Infra-Red (SWIR) are essential to effectively separate surface and aerosol effects over land. Spectral bands in the mid-visible and NIR are what primarily provide sensitivity to aerosol refractive index and particle size.
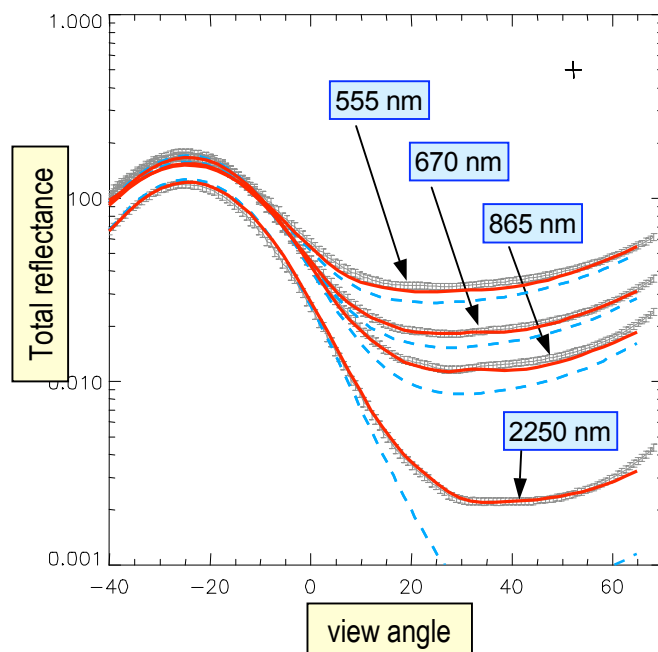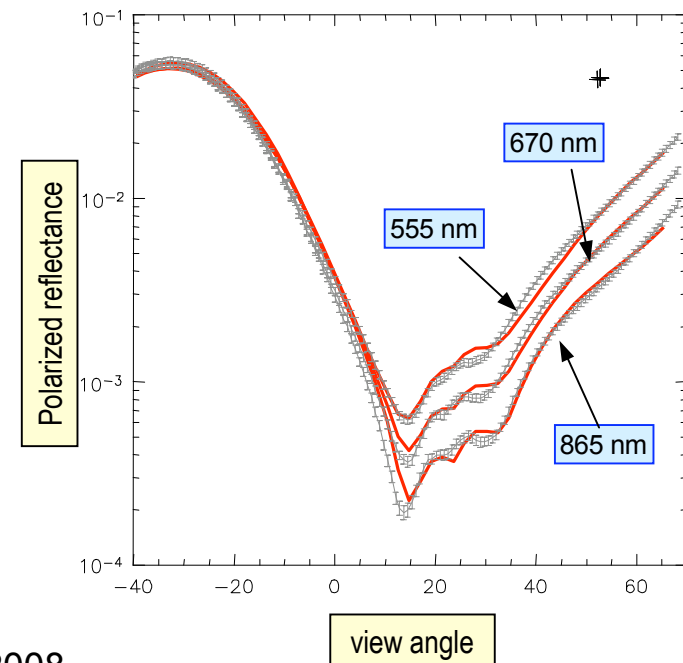
Retrieval Theory

– Spectral

• and to accurately estimate coarse mode properties (e.g. shape)
over ocean. In this example wind speed is 8 m/s, from the
West, chlorophyll concentration is 0.1 mg/m^3 (in agreement
with MODIS Aqua estimate) and a mixture of spheres and an
equi-probable distribution of spheroids is required for the
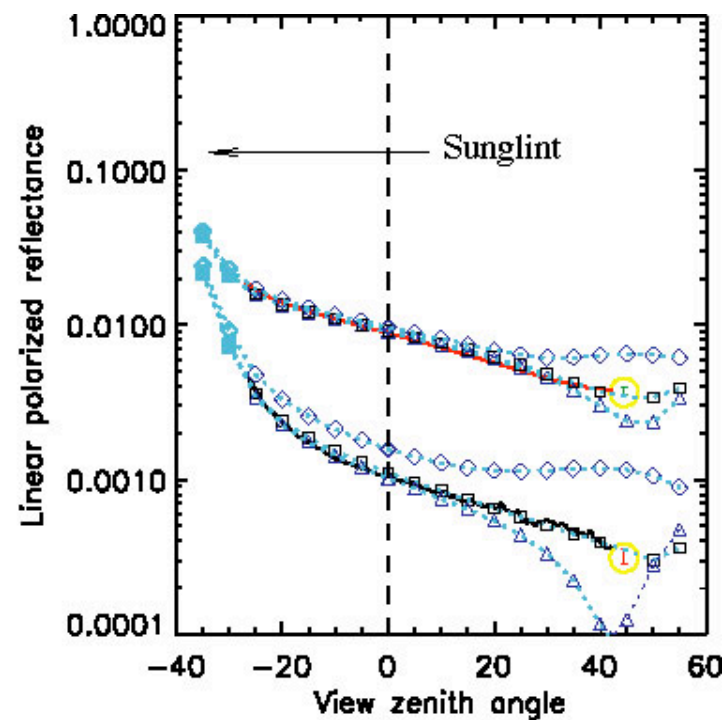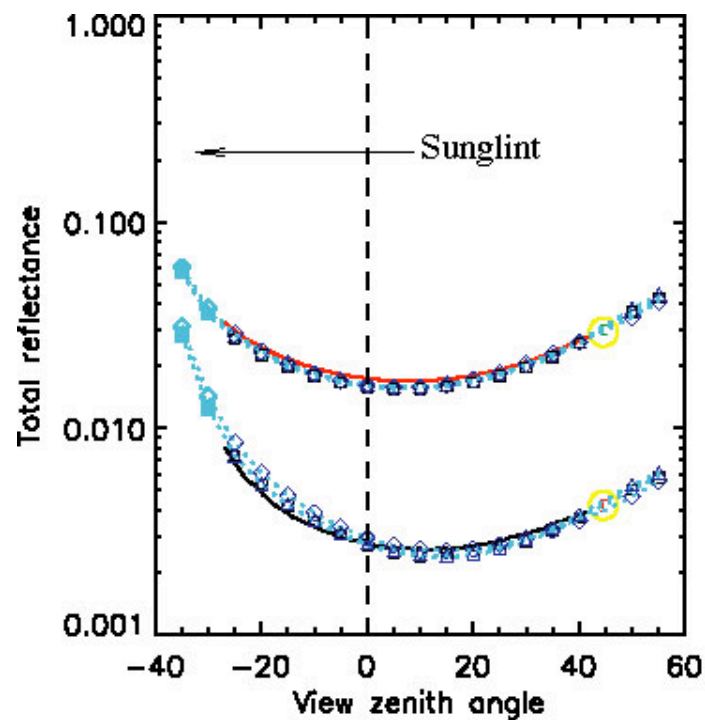coarse mode.

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Retrieval Theory

– Angular

- At a minimum an angular range of ±50 degrees is necessary to alleviate non-uniqueness issues.
  - Triangles (diamonds) demonstrate the result of increasing (decreasing) the coarse mode refractive index by 0.03 (0.09) from a best fit value.

Retrieval Theory

– Accuracy

- If a broad spectral and angular range of measurements are available then the calibration accuracy has a direct impact on the accuracy of the retrievals.

| Comments / Retrieval errors	σ_τ^f	$\sigma\_r_{eff}^f$ (× 10^{-3})	$\sigma\_m_r^f$	$\sigma\_\omega_0^f$
Reference (see section 4.1)	0.04	7.	0.0165	0.034
(-) Errors due to calibration uncertainty	0.025	4.9	0.012	0.027
(-) Errors due to radiometric noise	0.038	7.	0.0161	0.032
(-) Errors due to polarimetric uncertainty	0.0365	6.7	0.0157	0.031
(-) Errors due to the spectral dependence of the surface polarized reflectance.	0.04	7.	0.0165	0.034
(-) Errors of modeling	0.039	7.	0.0165	0.0335
Considering a polarimetric accuracy of 0.005 instead of (0.002 + 0.002 * Q/I)	0.061	9.	0.0235	0.052
Calibration errors spectrally and angularly correlated	0.025	5.1	0.0125	0.0275
Calibration errors spectrally and angularly correlated with a progressive decrease of the correlation in function of the wavelength and angle	0.07	10.	0.032	0.052

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Retrieval Theory

– Accuracy

- Accuracy must also be maintained for realistic scenes. For example for a design like APS within scene inhomgeneity causes a reduction in polarimetric precision of less than 0.5*relative_variability*IFOV_matching. Since the IFOV matching is 0.3% for the worst case APS bands even popcorn cumulus only affects the measurements by 0.15%.
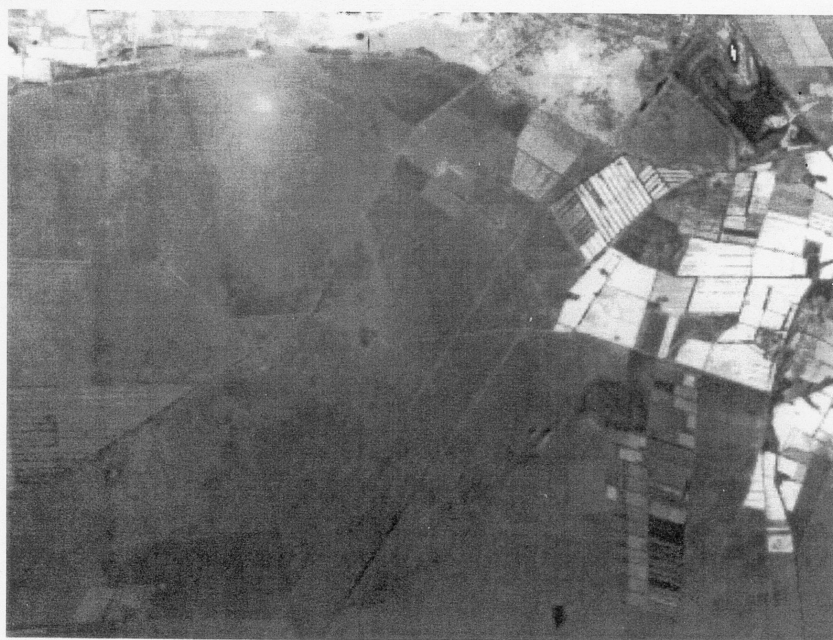
Figure 4. Example of Polarization and Directionality of the Earth Reflectances (POLDER) image data for radiance measurements at $\lambda = 865$ nm. Measurements acquired on June 23, 1991, over the area of La Crau. The middle part of the picture is the Centre National d'Etudes Spatiales calibration site consisting in bare soils (pebbles, sparse vegetation). The normalized radiances range from 0 to 0.40.
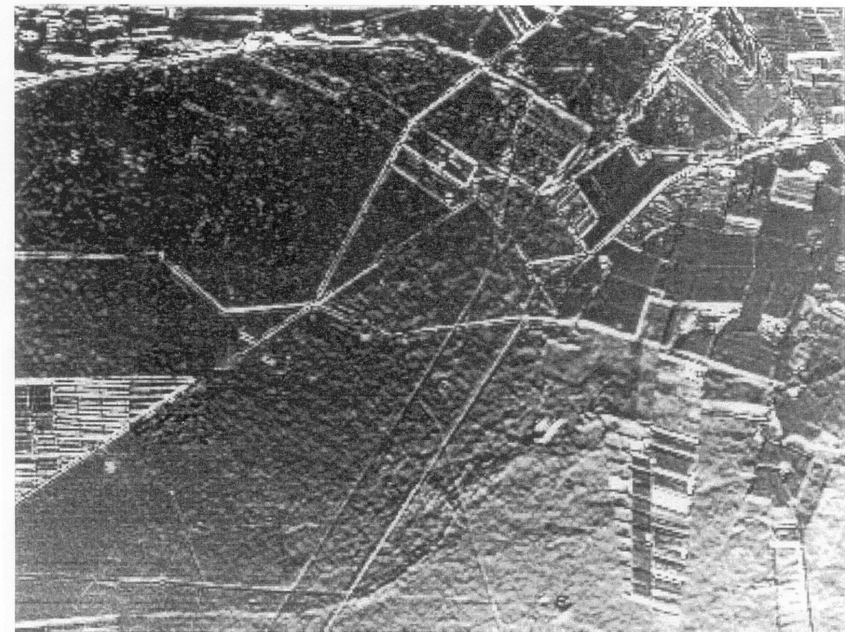
Figure 5. Same as in Figure 4 but for polarized radiance measurements. The normalized polarized radiances range from 0 to 0.015. The picture is a composite of three pictures acquired with different polarizers, which explains polarization artifacts due to misregistrations between adjacent areas with contrasted reflectances.
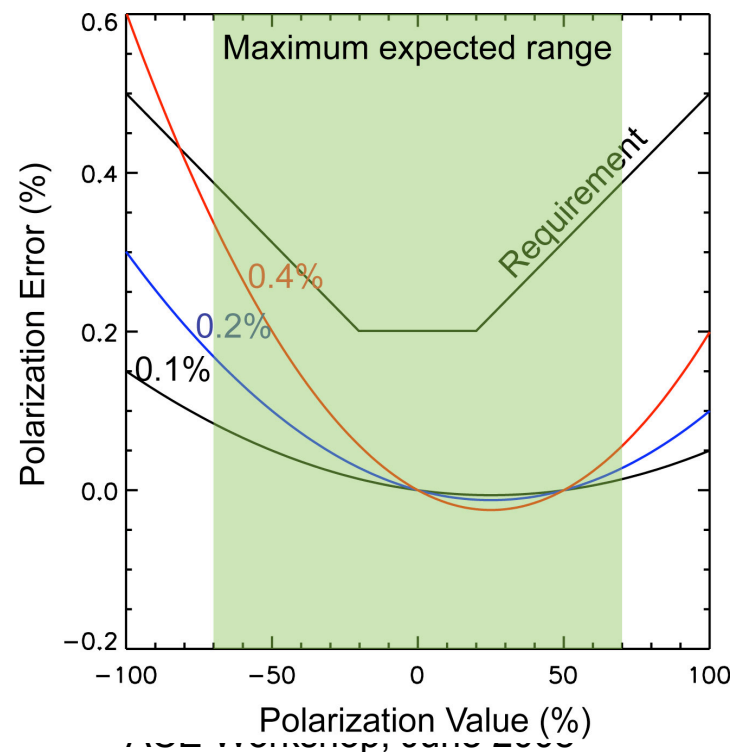
Retrieval Theory

– Calibration

- Polarimetric calibration using a weakly polarized scene and a highly polarized scene is extremely valuable. It is the polarimetric equivalent of a dark target and bright target. If you have such a calibration capability then even if the sensor degrades substantially on orbit the sensor performance can be maintained.

Retrieval Process

- – Assumptions
  - • Oceans
    - – Ocean color depends primarily on Chlorophyll concentration and the simultaneous retrieval of this parameter together with the aerosol retrieval allows for accurate aerosol retrievals.
    - – White caps are slightly blue, similar to Moore et al. rather than Frouin and wind speed is an adequate parameter to capture their average coverage.
    - – Cox-Munk shape but NOT the dependence of the shape on wind speed is adequate to model glint.
  - • Land
    - – Polarized reflectance is grey, reasonable spectral variation based on measurements of rocks and the wax that covers vegetation is included in model error covariance matrix.
      - » Has no effect at high aerosols loads and in the analysis of data taken under sever clear conditions still does not have an effect, since surface appears to have less polarized reflectance variation than worst case assumed.

Retrieval Process

- Approximations
  - Ocean
    - Anisotropy of sun glint is only included in the direct beam interaction with the surface. Inclusion of multiple, or diffuse, interactions means that Fourier decomposition in azimuth is not valid.
  - Land
    - Assume that the diffuse interactions between the polarization of a surface and the atmosphere can be represented by a scaled Fresnel polarized reflectance. Direct beam interactions are estimated using the longest wavelength band available.
  - Land & Ocean
    - Assume that thick aerosol layers have zero pressure thickness so that estimates of single scattering albedo and optical depth have a clear basis.
    - Use correlated k-distributions to model gaseous absorption, or create parameterizations for gaseous absorption in bands where it is very weak.

Retrieval Weaknesses

– Aerosol vertical distributions

- Polarization is not only sensitive to aerosol absorption in the blue/UV (like TOMS, OMI etc) but also allows you to get an estimate of absorption that is independent of aerosol transport model.

- The optical depth, SSA and layer top height can all be estimated quite accurately, but the layer base height that is assumed does affect the retrievals.

Effect of vertical extent of layer
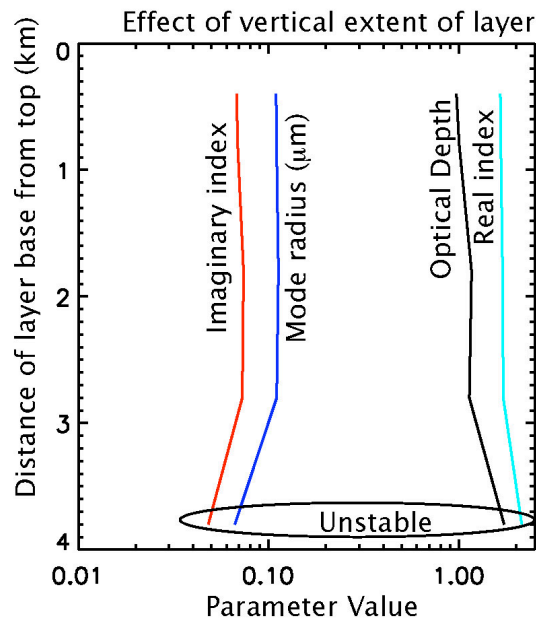
| Physical Thickness (km)	SSA	AOT	Mi	Ptop
1.2	0.85	0.56 (0.01)	0.032 (0.0015)	560 (10)
2.4	0.83	0.59	0.035	559 (10)

- Without lidar information, the best approach to the effect of layer base height is either to integrate the solutions over a climatology of layer thicknesses, or assume the layer has no pressure thickness which will give a low bias for AOT and a high bias for SSA.
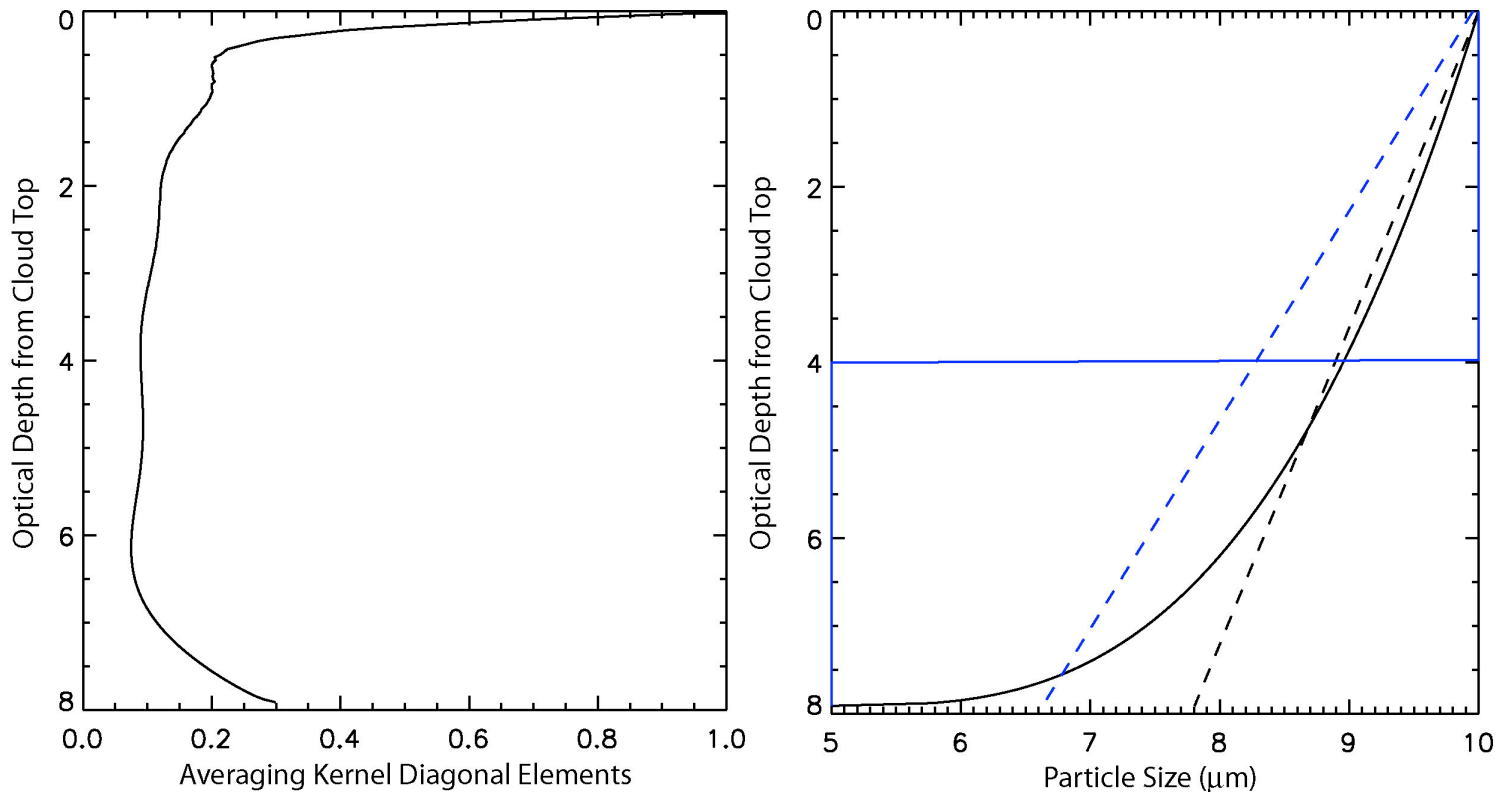
Retrieval Weaknesses

– Cloud vertical distributions

- Weighting functions for polarized reflectance and reflectance are very different.
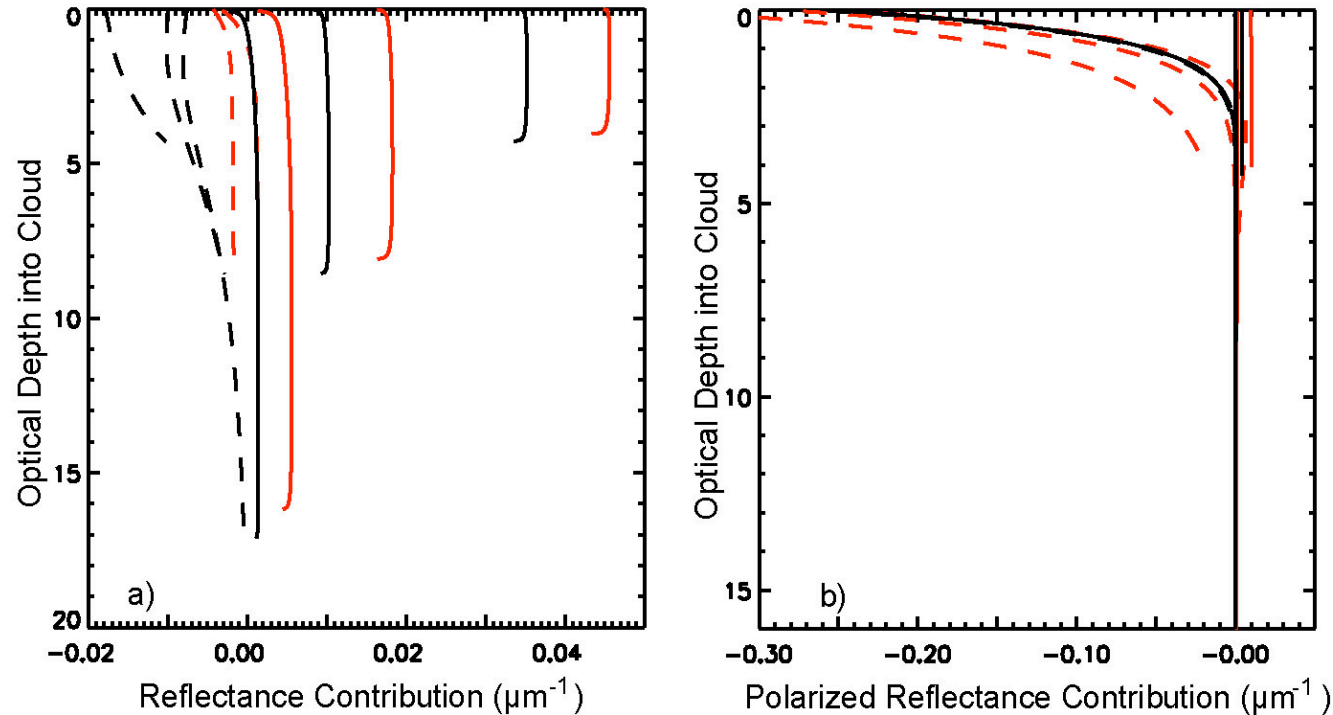
Retrieval Weaknesses

– Cloud vertical distributions

• But not sufficiently informative to actually estimate a vertical profile of size.

Improvements in ACE

- – Aerosol vertical distributions
  - • Whether a polarimetric, or UV approach to estimating aerosol absorption is used, having information from a lidar system that constrains aerosol layer boundaries, and provides an initial estimate of the vertical variation in microphysical properties will reduce the uncertainty in aerosol absorption enormously.

- – Cloud vertical distributions
  - • Cloud particle effective radius is not really a very useful tool for diagnosing the aerosol indirect effect. The number concentration of droplets is what is of primary interest. Having cloud radar combined with polarimetry provides an effective tool for analyzing clouds. This is because the polarimetric DSD estimate is for the largest particles in a well defined layer near cloud top and includes an estimate of DSD width. This is helpful when combining measurements that are sensitive to very different size distribution moments in order to estimate the number concentration of droplets.

Testing the components of ACE

- ARCTAS
  - ARCTAS, summer deployment to measure smoke plumes with in situ measurements by the NASA P3 and the NASA LaRC B200 flying above with the HSRL and the RSP. We will be able to evaluate how good/bad the remote sensing estimates of ssa are and how effective different lidar implementations are in reducing the uncertainty in the ssa.